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Space Sensors for Human Investigation of Planetary Surfaces (SpaceSHIPS)

Linda M. Miller, Cristina Guidi, Timothy Krabach*
Jet Propulsion Laboratory, California Institute of Technology
MS 302-306, 4800 Oak Grove Drive, Pasadena, California 91109
Phone: 818-354-0982
e-mail: Linda.M.Miller@jpl.nasa.gov

** NASA Kennedy Space Center*
AA-D, Kennedy Space Center, FL 32899

Abstract

Human exploration beyond low Earth orbit is typically characterized by cost-prohibitive launch vehicles, payloads, and by time consuming maintenance of space vehicles. NASA is currently in the process of alleviating some of these problems by investing in advanced developments in human health and performance, space transportation, space power, information and automation technologies, and miniaturization of sensors and instruments. In this paper, a roadmap describing microsensors and microinstruments needs, status, and technology gaps is described. Needs are broken down into several categories including science and engineering field labs; planetary prospecting; sample acquisition, curation, and planetary protection; crew environmental and medical monitoring; and system and vehicle health monitoring. In addition to scientific, crew and vehicle health and maintenance performance goals, innovative sensors and instrument technologies are chosen to conserve mass, power, volume and cost. “Smart sensor” or “System on a Chip” approaches are highlighted to alleviate an astronaut’s more mundane responsibilities and to increase the time for available scientific investigation. These approaches also have the potential to minimize bandwidth and data storage requirements. Distributed microsensor architectures are also considered to improve the safety and long-term reliability of spacecraft and mobile support systems by enhancing sensing capabilities without impacting mass or power budgets for communication. Distributed sensor networks also have the potential to improve system robustness through redundancy and reduce operator error through automation. These concepts will be reviewed and summarized in the context of the SpaceSHIPS timeline.

Introduction

In NASA’s Human Exploration and Development of Space (HEDS) Enterprise, the primary focus is to “bring the frontier of space fully within the sphere of human activity and to build a better future for all humankind”.[1] Safety, scientific exploration and affordable access to space are critical in fulfilling this vision. Planning a human presence in space is currently underway through a roadmapping activity to identify advanced technology re-

[1] NASA Strategic Plan 1998

quirements, existing efforts and gaps. For example, a human mission to another planet needs to accomplish three basic objectives: search for evidence of life, provide the capability of sustaining human life on another planet, and determine the feasibility of a permanent human settlement. Advanced sensors and instruments can be used to help in obtaining information and data pertaining to these goals. In the following pages, we will look at identified sensor and instrument requirements, some research efforts in progress, and point out some of the new trends that will enable human exploration beyond low Earth orbit.

Background

With the construction of the International Space Station (ISS) the HEDS enterprise is now assessing the feasibility of long duration human missions beyond Earth orbit. The Exploration Office at Johnson Space Center (JSC) is the focal point for coordinating a wide range of planning, assessment, and program development activities to prepare NASA and the nation for this next phase of human space flight to the Moon, near-Earth bodies, and Mars.

A key element of the Exploration Office efforts is identifying the necessary technologies that will enable human exploration of the solar system. This requires assessing the current status of the art, and identifying areas for future investment. To this end, JSC has constructed a "Technology Readiness" effort. It is partitioned into five thrust areas, each lead by a Technology Agent to track the progress of emerging technologies, and identify the state of readiness of each technology for human flight. The five thrust areas and associated NASA center leads are:

- ***Human Health and Performance*** (JSC) - advanced life support systems, habitation systems, extravehicular activities, surface mobility, and crew well being and training.
- ***Advanced Space Transportation*** (MSFC) - in-situ resource utilization, advanced interplanetary propulsion systems, cryogenic fluid management, and aeroassist technology.
- ***Advanced Space Power*** (LeRC) - advanced power generation, management and storage using solar power and nuclear power.
- ***Automation and Information*** (ARC) - emerging technology for communication and networks, advanced operations, intelligent systems and Intelligent Synthesis Environment (ISE).
- ***Advanced Sensors and Instruments*** (JPL and KSC) - sensors and instruments pertaining to science and engineering field labs, planetary prospecting, sample acquisition and curation, crew environmental/medical monitoring and system/vehicle health monitoring.

The Advanced Sensors and Instruments area is cross-cutting in nature, i.e. it all supports needs in the other four thrust areas. Sensors are necessary for all parts of a mission, from instruments that gather scientific data at the mission destination, to monitors that measure in exacting detail the environment where the crew lives for many months, to gathering the thousands of pieces of information that make a launch successful. However, current sensors and instruments fall short in many respects: current flight-qualified systems tend to be massive and power hungry, require complex cabling systems, and some are prone to failure (instruments are difficult to replace on a space mission. From a system perspective, large design infrastructure, operational awareness, and mission resources requirements must be minimized in all future sensor developments.

To meet these limitations, the Advanced Sensors and Instruments thrust is looking at incorporating breakthrough technologies[2-5] into the sensors and instruments roadmap for enabling human missions beyond low Earth orbit. The applicability of MEMS technologies, nanoscale-computing systems, and smart networks of robust sensors providing knowledge on demand, for instance, is clear. The challenges include the basic development of sensors, system integration, field-testing, verification, and flight validation to human space system reliability levels.

In the following sections, sensor needs are divided into four areas:

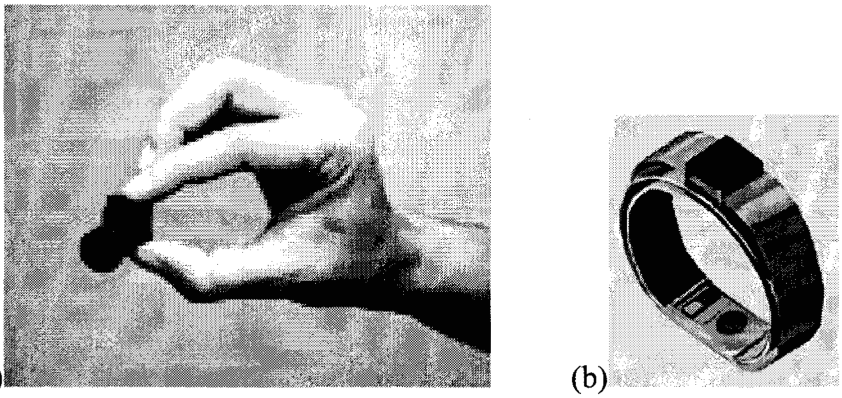
- ***Crew Environmental/Medical Monitoring***
- ***Science and Engineering Field Labs***
- ***Sample Acquisition and Curation***
- ***System/Vehicle Health Management***

Relevant research is reviewed to highlight the large potential gains in performance, mass, volume, and cost that advanced micro- and nano-technologies offer.

Advanced Sensors and Instrument Needs and Example Developments

Crew Environmental/Medical Monitoring

Human missions beyond low Earth orbit require careful attention to safety and crew medical care. Transit times and surface stays are likely to be on the order of two years which is significantly greater than any space stay ever experienced by a human. We do not currently have the long-duration space experience and knowledge of what effect microgravity has on the human body and what countermeasures should be taken, however we do know that microgravity alters normal bodily functions. Monitoring kidney and liver functions, muscle atrophy, and bone growth are examples of critical measurements required for long duration human missions. Likewise, acute and emergency care of astronauts will require a telemedical presence. Ingestible sensors that monitor the digestive tract, non-invasive sensors that monitor temperature, heart rate and perform blood analysis are being considered. All of these examples may be used to transmit data to an overall system that identifies the real-time health of the crewmember so that medical doctors on Earth or in a habitat can make an assessment of the care required. Miniature cameras like JPL's active pixel sensor (APS) camera[6] and Oak Ridge national Laboratory's finger-ring pulse oximeter,[7] both shown in Fig. 1, provide the technology for non-invasive monitoring which could be relayed to doctors on Earth for further evaluation.



(a) (b)

Figure 1. Examples of advanced medical monitoring systems: (a) all digital miniature camera and (b) artist's concept of Oak Ridge National Laboratory's finger-ring pulse oximeter.

To insure safety of the crew, environmental monitors are essential. Internal atmospheric conditions within the spacecraft, habitat and/or mobile environment must be maintained to stringent specifications. Air and water are closed cycle systems requiring proper recycling and quality management. The air quality for the internal atmosphere needs to be at the proper gas concentration, temperature, humidity, and purity levels, i.e. toxin-free. Likewise, the water quality and food environments need to be meticulously monitored for microbial activity. For air, water and food, an alarm system must be incorporated to enunciate a violation of the environmental requirements so that remedial action can be initiated. Some examples of the myriad of measurements required to maintain a safe environment for the crew are listed in Table I.[8]

Depending on the mission, radiation hazard alarms are also needed to alert the crew of the presence of highly charged energetic particles and galactic cosmic rays. "Early warning" systems, such as solar flare monitoring systems, are critical to mobilize the crew to an area within the surface base that is safe from the radiation hazard.

Once the safety and medical systems are in place, space exploration utilizing human creativity and decision-making skills and dexterity are of primary interest in the development of advanced sensors and instruments for HEDS.

Science and Engineering Field Labs

The Science and Engineering Field Labs category includes instruments that may be assist the human explorer in answering fundamental science questions:

- What is the origin and evolution of solid planets?
- What is the origin and evolution of the atmosphere?
- What is the potential of a planet harboring life?
- What is the potential of another planet being a future home for humans?

TABLE I. Examples of Acceptable Levels in Crew Environmental Monitors

Category	Measurand	Acceptable Levels
Potable Water		
Physical		
	pH	6-8
	total solids suspended/dissolve	100 mg/L
Inorganic		
	NH_3	0.5 mg/L
	As	0.01 mg/L
	Cd	0.005 mg/L
	Cr	0.05 mg/L
	Pb	0.05 mg/L
	Mn	0.05 mg/L
	Hg	0.002 mg/L
	Ni	0.05 mg/L
	Se	0.01 mg/L
	Ag	0.05 mg/L
	Sulfide	0.05 mg/L
Organic		
	halogenated hydrocarbons	10 mg/L
	phenols	1 mg/L
	uncharacterized total organic carbon, TOC	100 mg/L
Organic Constituents		
	benzene	5 mg/L
	CCl_4	5 mg/L
	1,2-dichloroethane	5 mg/L
	trichloroethane	5 mg/L
	tetrachloroethane	5 mg/L
	1,2-dichloropropane	5 mg/L
	vinyl chloride	2 mg/L
Microbial		
	total bacteria	100 CFU/100mL
	coliform bacteria	<1 CFU/100mL
	virus	<1 CFU/100mL
Air		
Comfort Levels: habitats, space suits, vehicles	partial pressure of CO_2	max 400 N/m^3
	partial pressure of O_2	max 400 N/m^3
	temperature	291.5-299.9 K
	Dew point	277.6-288.7
	ventilation	0.076-0.203 m/s
	pressure	100k-101.4 kPa
	micro-organisms	500 CFU/ m^3
	particulates <0.5 mm	max $3.35X10^6$ count/ m^3

A human mission to another planet will consist of performing field studies either by a crewmember on the surface, a mobile robot such as a rover or aerobot, or a combination of the two, via telepresence on the planetary surface. Areas of interest include geology, geophysics, exobiology and space physics, and engineering sensors and actuators to support the mobile laboratories. From a geological standpoint, panoramic imaging, chemical and mineralogical analyses, spectroscopy and microscopy are required to build a working knowledge of the landing site and of potentially interesting field laboratory sites. Meteorological monitoring, seismic analysis, electromagnetic sounding and radioactive analysis aid in the understanding of the geophysics of the area. This information also provides critical information about the subsurface structure as well as the presence of water or ice. Finally, chemical, mineralogical, isotopic, and geochronological analyses all support the search of prebiotic, extinct or extant life.

There have been many advances in areas described above to reduce mass, volume, and cost while maintaining performance goals. Miniature seismometers[9] have been demonstrated with a noise floor below 5 $ng/\sqrt{Hz}$ and power consumption less than 2 mW. A geochronology lab, a micro NMR, a miniature electron probe analyzer, a Raman spectrometer, a Computer Tomography Imaging Spectrometer (CTIS), and an X-ray Diffractometer/Fluorescence Spectrometer (XRD/XFS) are some examples of current development projects[2] at NASA's Jet Propulsion Laboratory for mineralogical analyses. To study meteorological variations including particle size and distribution, micro weather stations,[10] micro LIDAR, and Laser Doppler Anemometers (LDA) are also being developed. The search for life is being pursued through several avenues including a capillary electrophoresis system for the study of amino acids, Stable Isotope Laser Spectrometer (SILS), and Gas Chromatograph/Mass Spectrometer.[11] Examples of these efforts are shown in Fig. 2.

Instruments such as those listed above are in various stages of development or technology readiness levels (TRLs). Technologies such as MicroElectroMechanical Systems (MEMS), LIGA, nanotechnology, wireless communications, miniature power sources, network science, smart materials and structures will all enable future advancements. However, beyond performance issues such as sensitivity, accuracy, power budgets, etc. are issues of robustness, reliability, and safety. Packaging, fault tolerance, and radiation hardness are all areas that require additional focus[14] in the final drive towards human exploration beyond low Earth orbit.

In addition to breakthroughs in sensors and actuators, system architecture advancements are needed to maximize system utility. For example, smart sensors and entire "systems on a chip"[15] are being developed which analyze data and return only pertinent information. This not only reduces telecommunication bandwidth requirements, but also reduces data storage and potentially improves the reliability and robustness of the overall system. Wireless sensors and instruments also offer benefits by reducing cabling requirements and by increasing the effective area of the measurement if they are combined in a network of sensors.

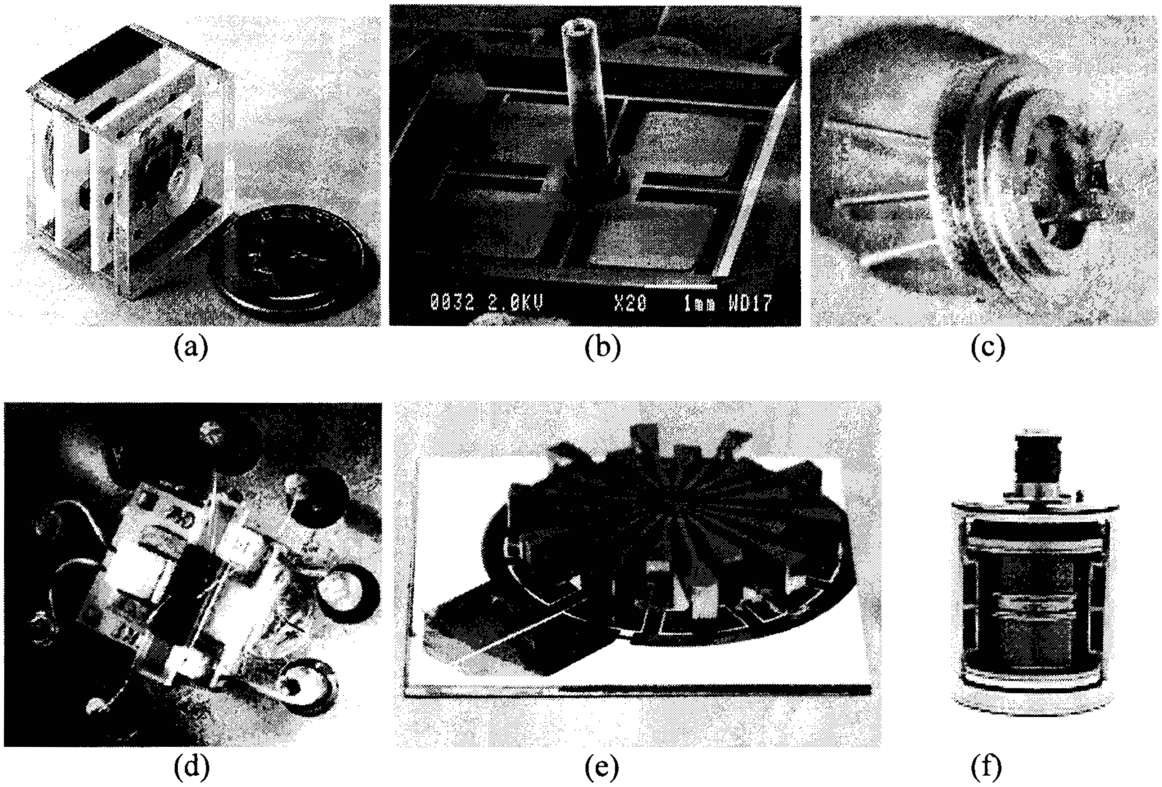


Figure 2. Examples of miniature sensors and instruments currently in progress to support science and engineering field laboratories: JPL's (a) Active Pixel Sensor (APS) Camera, (b) micromachined microgyroscope,12-13 (c) tunable diode laser (TDL) used in gas detection spectroscopy, (d) surface acoustic wave (SAW) hygrometer used in micro weather station, (e) LIGA-based micro mass spectrometer, and (f) sock tolerant seismometer based on GeoSpace Corp. geophone.

Planetary Prospecting

Site selection for human habitation is critical for crew safety and science return. Therefore, samples obtained from the precursor robotic missions and the first human mission must be screened to assure maximum information to answer pertinent scientific and engineering questions. Areas that are geologically diverse are prime candidate settlement sites. Initial reconnaissance missions to determine topology, mineralogy, water sources, etc. might support multispectral imaging and spectroscopy similar to instruments discussed in the science and field engineering labs, however, at a lower resolution and wider field of view.

An additional factor that needs to be addressed by instruments in Planetary Prospecting is evaluating the planetary resources to support human life. Human exploration on a planetary surface is likely to necessitate an extended stay for both scientific endeavors and because of transportation logistics. Given an extended mission, additional mass is required to support life unless resources can be extracted from the planetary surface. Therefore, identification of natural resources is very important. Examples of in-situ resource utilization include the conversion of the planet's atmosphere into fuel for an ascent rocket launch, materials for life support systems in a human habitat, extraction of minerals from regolith for tools, or mining of fuels or minerals from subsurface sources. The need for water and a reliable energy source also necessitate the search for a hydrothermally active region. Not only is a hydrothermal region of necessity for establishment of a human settlement, it is also a scientifically rich area for exobiology research.

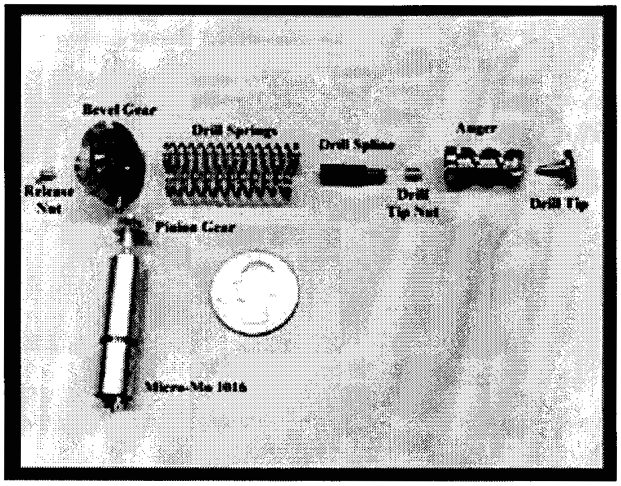
The method of searching out these scientifically interesting and resource-rich areas may be accomplished by several methods. Imaging and remote sensing to identify resource-rich areas can be performed from an orbiting spacecraft, a plane, or from a balloon several hundred meters above the surface transferring information to a surface habitat for review by a crew member. This imaging can be a great asset in mission planning.

In planning the rover expedition, spectral images from a distance or above the surface to survey the terrain can identify interesting locations for follow-on close-up investigations using rovers. Piloted rovers can also accomplish planetary prospecting with scientific instruments mounted for investigation of the surface. The rover would need instruments that provide the capability to perform petrography, mineralogy, major and minor chemistry, volatile chemical analysis, and various modes of spectroscopy and microscopy. The main purpose of performing planetary prospecting is to provide the best-suited sample for investigation at the base laboratory and eventual return to earth for further examination.

Sample Acquisition and Curation

Once a potentially valuable sample has been screened as a good candidate for further examination, the acquisition and preparation of the sample must not alter its natural state while in its original environment. Accurate documentation must elucidate the surrounding mineralogy, electromagnetic environment, atmospheric conditions, and overall topology.

When studying regolith, both the outer patina and the inner, presumably unweathered core are of interest. The patina provides information on weathering, chemical reactions, radiation and aging, while the inner core gives clues to mineralogy, exobiology, etc. In any case, a fresh rock surface is necessary to obtain accurate information. Several methods such as dust removal, laser ablation, surface grinding, coring, fracture or pyrotechnic methods can accomplish this. Much work is currently underway in low power coring and drilling methods. One such example is a miniature drill assembly launched January 3, 1999 in the Mars Microprobe, and shown in the photograph of Fig. 3. This configuration is small, shock tolerant, and low power.



Motor / Drill Assembly

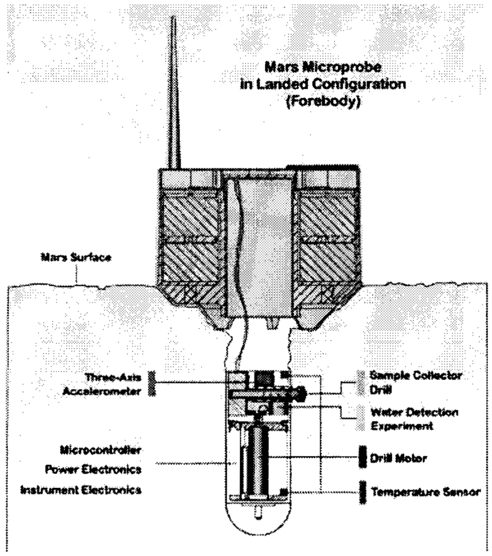


Figure 3. Miniature motor and drill assembly installed in the Mars Microprobe forebody as shown in the adjacent schematic.

System/Vehicle Health Management

The largest part of a mission's cost can be associated directly with the cost of operations and maintenance of subsystems for launch vehicles, crew habitats and supporting subsystems such as the In-situ Propellant production plant and life support systems. Approximately 20% of the entire mission's price tag are attributed to the processing and maintenance of these support systems. Not only is cost an important factor to minimize, but also the valuable crew time spent of routine operations. Although the planned mission has the crew spending over 500 days on the surface, most of the time should be spent collecting valuable science data. Therefore a system that will allow the astronaut to dedicate his/her time performing these scientific investigations rather than performing maintenance would make the mission more efficient. In order to realize some cost and time-saving in the overall mission, while also increasing the safety and reliability, System/Vehicle Health Management (SVHM) systems can by employed. By incorporating modern non-intrusive sensing technologies into the various subsystems of a vehicle or spacecraft, the visibility into a safety critical system is significantly improved by early detection and/or prediction of a potential component failure. By using the predictive capabilities of real-time monitoring of subsystem health, two important objectives are realized: 1) valuable crew time is not expended performing mundane maintenance tasks and problem isolation, and 2) the extension of the replacement of life-limited components.

Based on the planning scenario currently adopted for the human mission beyond low-earth orbit, there are several generic health management systems that will be needed which include leak detection systems, structural health systems, fluid processes health systems, spacecraft environment monitoring systems, electrical component health systems and active/dynamic structure systems.

The leak detection system would be responsible for detecting leaks from the subsystems of the various space transportation stages, i.e. propulsion systems, active cooling systems, and habitat integrity. Commodities that would need to be measured would include, hydrogen, oxygen, methane, hydrazine and freon. Ideally, the leak detection system would be coupled with sensor fusion so that when an alert condition is detected, remedial action can follow based on the data sensed by the detection sensors.

Insight into the environment that the launch vehicle and spacecraft is subjected to can help estimate its structural "age" and lifetime. The structural health system would monitor the health of the structure itself such as the integrity of a pressure vessel when a loading or "stressing" environment is applied such as strain, vibration, acoustics, shock, acceleration, pressure, temperature and even corrosion.

Fluid processes such as propellant production, processing, and transfer need to be managed also to assure efficient use of the available commodities. Measurements of interest would include pressure, flowrate, temperature, liquid quantity and quality, purity and the chemical species.

For human exploration missions, it is very important to assure the safety of the crew while in transit to the desired destination point, therefore, it is very critical to understand and avoid harmful environments to the crew. The spacecraft environment monitoring system would monitor the natural space environment and its effects on the spacecraft. Items of interest include atmospheric density, atomic oxygen, ionizing radiation, plasma, solar activity, gravitational field, electromagnetic fields, meteoroids and orbital debris.

Electrical Component Health System would monitor the state of valves and actuators. By using current signature and voltage signature techniques along with position indicators, real-time knowledge of the health of the system can be analyzed for advanced notice of a component failure.

Active/Dynamic Structure Systems would encompass "smart structures". Smart structures can be passive, reactive or adaptive. Passive smart structures would be structures that have sensors embedded within the material that provide information about the state of the structure. Reactive structures contain the same sensors as the passive material however this structure can now react by changing the shape or position of the material. Adaptive structures are those that include passive materials and a control system to perform corrective action based on the sensory input while also learning from the inputs. An example of an application of adaptive structure systems for the planned human mission would be for use on the large solar arrays of the transportation stage. These structures are very large and need a dampening system to reduce oscillation of the arrays that may eventually damage the array structure. Potential smart sensors to be used within materials to provide this capability include acoustical, microelectronic, piezo-electric and optical fiber sensors.

In general, all of the above-mentioned systems will be comprised of multi-parameter sensors that incorporate some sort of sensor fusion algorithms so that the System/Vehicle Health Management system will provide the crewmembers or system operators with "knowledge" rather than data. Autonomous operation to provide the corrective action is also highly desired so that quick remedial action can occur should a crewmember not be available. Another desired attribute for the SVHM system would be wireless technology so that mass reductions can be realized by the elimination of bulky wire harnesses. Typical examples of cutting-edge technology that can be applied to a new vehicle or system design for better insight into the operation and health of a systems would include but is not limited to fiber optic communications and sensing, Micro Electromechanical Systems (MEMS), auto-calibration and data cross-checking sensors, neural networks and sensor fusion.

Sensor and Instrument Attributes

Despite the diversity of system needs outlined above, there are common themes running through the list of attributes that sensors and instruments will be required to possess for human exploration missions. The key attributes that will be needed in the sensor and instrument systems described above are:

Reduction of mass, volume, and power requirements – While the mass, volume and power of sensors in a manned mission may at first appear to be too small to have a large effect in overall system mass reduction, a closer look proves otherwise. Figure in support structures needed to hold sensors in place, enclosures to hold and protect the sensors, and the inefficiencies and complexities of delivering power to each sensor (think numerous, large, inflexible power cables), and the full cost of the sensor to the systems becomes apparent. Advanced sensors and instruments will be developed with goal of reducing mass, power, and volume by orders of magnitude in many cases, leading to a rippling effect throughout the system that will provide meaningful mass reductions in manned systems. For example, ultra low power sensors could be combined with novel "energy harvesting" systems to give designers subsystems that draw power from the thermal environment, leading to completely wireless systems that can relocated on demand.

Increases in reliability, robustness, and calibration – The advent of MEMS and associated technologies is expected to lead to greater sensor reliability and robustness. One consequence of designing very small sensors is the improvement seen in shock resistance – there is simply too little mass and the moment arms are too short to provide any inertia for acceleration transients to have any effect. Additional system robustness can be gained through the use of multiple sensors; if the system cost of additional sensors can be driven down by a factor of 100, then gaining robustness through fault tolerant networks of sensors can be realized.

Finally, the long term accuracy and calibration of the sensors will be critical for the missions contemplated for long term human exploration. In many cases, these sensors will be inactive for months to years, yet will be required to operate within specification upon activation – sometimes in life and mission critical situations. The development of sensors that are self calibrating, possess low to zero drift, and will not require any user intervention is necessary for future NASA missions.

Ability to network and easily interface with the crew – Sensors, by themselves, are only the leading edge of the information flow to the spacecraft controllers and crew. A complete solution will require that sensors possess the ability to seamlessly and quickly network with each other and the overall system. Coupling this capability for easy network insertion with the concept of "peel and stick" sensors using "system on a chip" technology will provide astronauts the ability to reconfigure entire sensor networks in flight or on the surface as needed. This capability will also increase mission reliability and planning: such sensors can be reused again, possibly even for situations not imagined in the initial mission design.

Summary

The development of the advanced sensors and instruments described above is just beginning to be developed by NASA and others. New system architectures, scientific capabilities, and improved human-machine interfaces will result from these activities. The advent of the capabilities described in this paper will offer profound changes in the design, operation, robustness, and cost of human exploration in the 21st century, and bring closer the goal of a widespread human presence in our solar system.

Acknowledgements

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